The LISA Mission Design

W. M. Folkner* for the LISA Team

* *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA*

Abstract: The Laser Interferometer Space Antenna (LISA) will be capable of detecting gravitational waves with frequencies from 0.1 mHz to 1 Hz by using laser interferometers to monitor changes in the distances between test masses in spacecraft separated by five million km. LISA will detect strains as low as 10^{-23} with a one year observation time and a signal-to-noise ratio of five. The sensitivity will be sufficient to detect gravitational waves from sources connected with massive black holes in the centers in many galaxies, and from many binary systems within the Milky Way galaxy. Under the concept presented, LISA will be formed by three spacecraft at the vertices of an equilateral triangle. The orbits are chosen so that the triangle formation trails the Earth by 20 degrees. Each spacecraft will contain two independent payloads containing a test mass, laser and 30 cm diameter telescope for the transmission and reception of laser signals. Two independent Michelson interferometers will be formed allowing both polarizations of gravitational waves to be detected.

INTRODUCTION

The goal of LISA (Laser Interferometer Space Antenna) is to detect and study low-frequency astrophysical gravitational radiation. The data will be used for research in astrophysics, cosmology, and fundamental physics. LISA is designed to detect the gravitational radiation from regions of the universe that are strongly relativistic, e.g., in the vicinity of black holes. The types of exciting astrophysical sources potentially visible to LISA include extra-galactic massive black hole binaries at cosmological distances, binary systems composed of a compact star and a massive black hole, galactic neutron star-black hole binaries, and background radiation from the Big Bang. LISA will also observe galactic binary systems, which are known to exist.

The effect of a gravitational wave passing through a system of free test masses is to create a strain in space that changes distances between the masses. The LISA mission will comprise three spacecraft located 5×10^{6} km apart forming an equilateral triangle. LISA will detect gravitational wave strains down to a level of order 10^{-23} in one year of observation time by measuring the fluctuations in separation between shielded test masses located within each spacecraft. The test masses will be shielded from extraneous disturbances (e.g., solar pressure) by the spacecraft in which it is accommodated so that changes in separation will be due to gravitational forces only. Laser interferometry will be used to measure the separation between the test masses with an accuracy of 10 picometer/$\sqrt{\text{Hz}}$ over the frequency range of 10^{-4} to 10^{-1} Hz.

Figure 1 shows the sensitivity to gravitational waves for the LISA mission and some of the expected signals from galactic binaries. The solid line indicates the LISA sensitivity limit based on measurements of the distance between spacecraft separated by 5 million kilometers with 20 picometer/$\sqrt{\text{Hz}}$ accuracy. The sensitivity from 3×10^{-3} Hz to 3×10^{-2} Hz is limited by the shot noise in the laser interferometer system used to make the distance measurements. The sensitivity for frequencies higher than 3×10^{-2} Hz is also limited by shot noise but with degraded response because the gravitational wavelength is less than the distance between the spacecraft. At frequencies below 3×10^{-3} Hz the sensitivity is limited by noise forces on the test masses within each spacecraft used as reference points for the distance measurements. Source strengths and frequencies for several known binary star systems are shown, as are those for several known interacting white-dwarf binaries (e. g. AmCVn). Within the LISA sensitivity range, thousands of close-white-dwarf binary(CWDB) systems are expected to be observed. At lower levels there may be so many binary systems that their signals cannot be distinguished, which may lead to a confusion noise limit indicated by the dashed line.

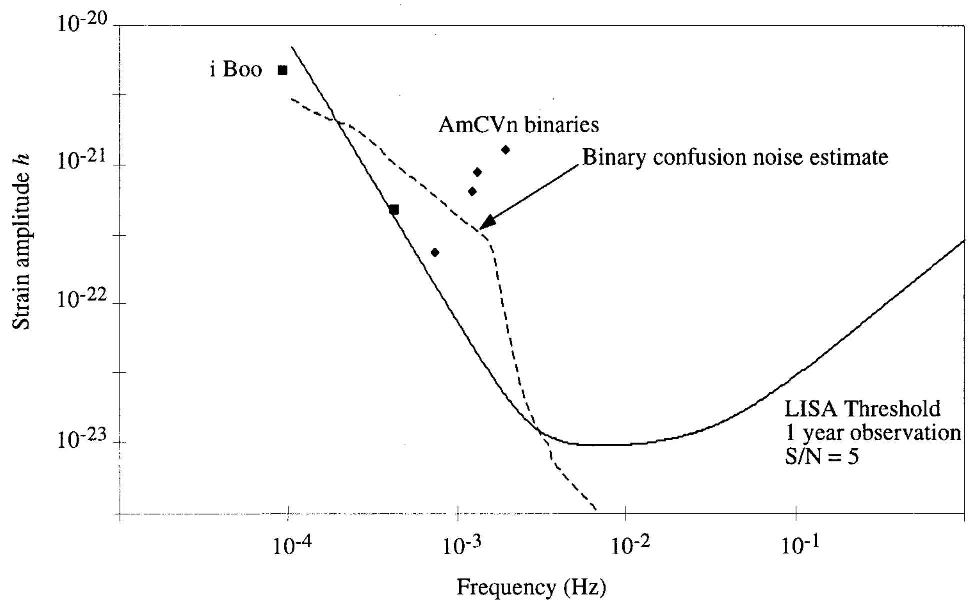

FIGURE 1. LISA sensitivity

MISSION DESIGN OPTIONS

The mission design for LISA has evolved through several configurations. Earliest mission concepts focused on forming a single Michelson interferometer with a central main spacecraft transmitting light to, and receiving light from, two distant spacecraft functioning as the mirrors at the ends of the arms of the interferometers (1). A later option studied was to split the central spacecraft into two, so that there would be four identical spacecraft with two spacecraft close together forming the central part of the Michelson interferometer (2). From this concept the idea of using six spacecraft of identical design arose with two spacecraft at each vertex of a triangle formation (3). The advantage with six spacecraft is that two independent Michelson interferometers can be formed using two of the vertices as centers of separate Michelson interferometers. (The information from the third possible Michelson interferometer would be linearly related to the other two.) This has the advantage of providing measurements of both possible polarizations of gravitational waves. Also, if one of the six spacecraft failed, the remaining spacecraft could still be used to form a single Michelson interferometer and continue observations.

A key issue in the mission cost is the number of spacecraft and the degree of reliability needed for each spacecraft. The mission design presented here is based on the philosophy that each spacecraft should be robust, with no single-point failure modes. Then the mission cost is minimized by having three spacecraft of identical design with backup spacecraft and payload systems. The three spacecraft each transmit and receive laser signals from the other two spacecraft with independent instruments. With all systems operational, two independent interferometers would be formed to observe both gravitational-wave polarizations. If any payload element leads to failure of one instrument, the mission would degrade gracefully into a single interferometer.

ORBIT SELECTION

The LISA laser interferometry measurements will be more difficult to make if the distances between spacecraft are not nearly equal. Thus the preferred orbits are chosen to minimize changes in the distance between spacecraft. The nominal orbits are shown in the Fig. 2a. Each spacecraft will be in an Earth-like orbit with a period of one year going around the Sun. The spacecraft orbits will be slightly elliptical and slightly tilted with respect to each other and with respect to the plane of the Earth's orbit (the ecliptic). By careful choice of the tilts of the orbits, the three spacecraft will maintain a triangular configuration even though each will be separately orbiting about the Sun. Figure 2b highlights the motion of one of the spacecraft and indicates how the distance between spacecraft remains the same and how the triangular formation changes orientation over one year. The change in orientation of the triangle formation is helpful in determining the direction of the sources of observed gravitational waves.

Changes in the spacecraft separation will be caused mainly by the gravitational pull of the Earth. The location of the center of the formation 20 degrees behind the Earth represents a compromise between the desire to reduce the gravitational pull by the Earth and the desire to be closer to the Earth to reduce the amount of propellant needed to reach the operational configuration and to ease the requirements on the telecommunications system. With these orbits, the angle between the two distant spacecraft, as seen from any one spacecraft, will change slowly through the year, by $\pm 1°$. This will require the angle between the two instruments on each spacecraft to be adjustable.

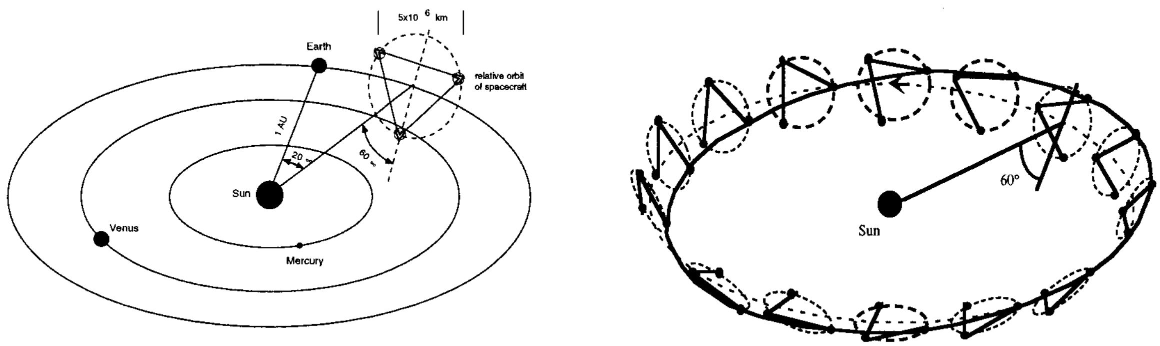

FIGURE 2.a) Initial orbit configuration for the three LISA spacecraft. b) Evolution of orbit configuration over one year. The figures are not to scale. The separation between spacecraft is actually 1/30 of the Sun-Earth distance.

SPACECRAFT DESCRIPTION

The spacecraft design is based on a short structural cylinder 1.8 m in diameter and 0.48 m high. Figure 3a shows an artist's concept of the spacecraft design. The cylindrical shape is efficient for attaching multiple spacecraft together on a single launch vehicle. The cylinder is as short as possible while still accommodating the 30 cm telescopes of the instrument, and as large in diameter as allowed by the launch vehicle's shroud, to maximize resistance to vibration during launch. The cylindrical structure supports a Y-shaped tubular structure which contains the two instruments. The spacecraft equipment will be mounted on the inside wall of the structural cylinder. A sun-shield will extend out from the top of the structural cylinder. During science operations the sun will be 30 degrees from the normal to the top of the cylinder and the sun shield will keep sunlight off the cylinder wall. The main solar panels for the spacecraft will be mounted on this sun shield. A cover across the top of the cylinder (not shown in the artist's concept) will prevent sunlight from striking the Y-shaped structure. The Y-shaped structure is gold-coated and suspended by fiberglass bands from the spacecraft cylinder to thermally isolate it from the spacecraft. The optical assemblies in turn are thermally isolated from the payload thermal shield. The spacecraft cylinder and payload thermal shield are made of a graphite-epoxy composite chosen for its low coefficient of thermal expansion. Two 30 cm diameter X-band radio antennas (not shown) will be mounted to the outside of the spacecraft for communication to the Earth.

INSTRUMENTATION

Figure 3b shows a cross-section of the two instruments. Each instrument contains a 30 cm diameter telescope (f/1 Cassegrain) for transmission and reception of laser signals to another spacecraft. Each instrument also has an optical bench, machined from a block of Ultra-Low Expansion glass with dimensions 20 x 35 x 4 cm, which contains injection, detection and beam shaping optics. An inertial sensor is mounted to the center of each optical bench, containing a test mass shielded from non-gravitational disturbances and a capacitor plate arrangement for measuring the position of the spacecraft with respect to the test mass. The interferometer measures changes in the distance between test masses in the different spacecraft. The spacecraft is kept centered on the test masses, based on the capacitive measurements and using small ion thrusters, to keep motions of the spacecraft from disturbing the test masses. The two instruments are supported at the front by pointing actuators near the telescope primary and by flexures at the other end to allow the angle between them to be changed as the spacecraft configuration changes.

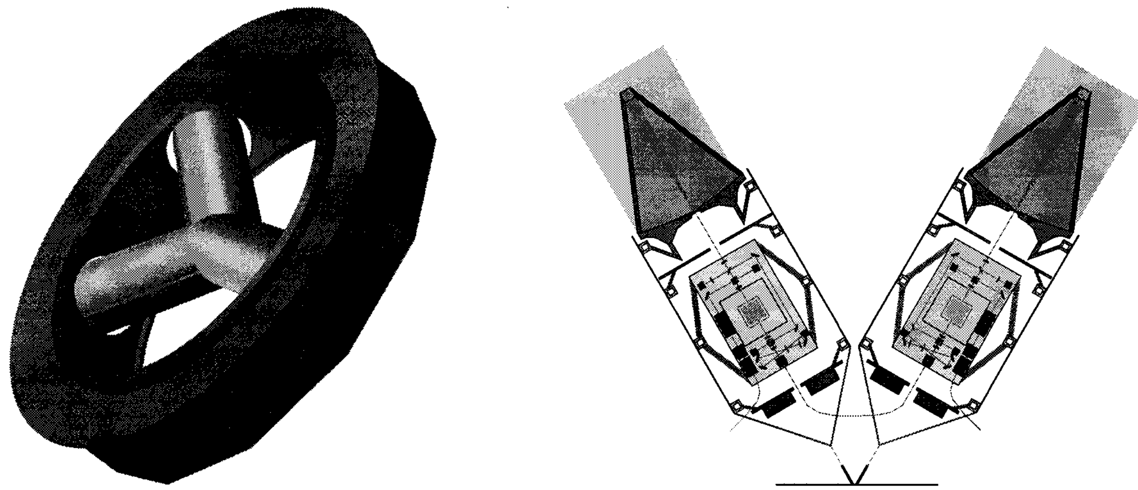

FIGURE 3.a) Artist's concept of the LISA spacecraft. Not shown is a cover over the top of the cylinder that prevents sunlight from striking the Y-shaped payload enclosure. b) Cross section of the two optical assemblies comprising the main part of the payload on each LISA spacecraft. The two assemblies are mounted from flexures at the back (bottom of figure) and from pointing actuators (not shown) at the front, near the primary mirrors.

LAUNCH CONFIGURATION

The three LISA spacecraft are designed to be launched on a single Delta-II 7925H rocket. Figure 4a shows the launch configuration. At launch, each spacecraft will be attached to a propulsion module that will, after launch, be used to guide the three spacecraft into their individual orbits. The three LISA spacecraft and propulsion modules will be stacked vertically inside the launch vehicle's payload envelope. The launch configuration has a propulsion module on the top of the launch stack.

The three spacecraft will be injected into an Earth-escape orbit by the launch vehicle. The Earth-escape orbit will cause the three spacecraft will slowly drift behind the Earth. After launch and injection to the Earth-escape trajectory, the three spacecraft with their propulsion modules will be separated and individually targeted to their desired operational orbits.

The thrust necessary to reach the final orbit configuration will be achieved through solar-electric propulsion, where electrical energy from converted sunlight is used to ionize and accelerate atoms in the direction of the desired thrust. This system requires much less mass at launch than a traditional chemical propulsion system and allows the mission to be launched on a smaller (and less expensive) launch vehicle.

TRANSFER PHASE

Because the solar-electric engines will only be needed to slightly change the tilt of the orbit and then to stop the slow drift with respect to the Earth induced by the launch vehicle, the engines can be smaller than those developed for delivering spacecraft to other planets. The LISA mission can use engines developed for keeping large communications satellites in proper geostationary orbit, some of which are already in use. The electrical power needed for the solar-electric engine is more than can be provided by the solar panels for the science part of the mission. The electrical power will be generated by two circular solar arrays that will be stored within the propulsion module at launch and then deployed to power the engine. Figure 4b is an artist's representation of one LISA spacecraft attached to its propulsion module with the solar panels deployed.

After reaching the final orbits, about 13 months after launch, the propulsion modules will be separated from the spacecraft to avoid having excess mass, propellant, moving parts, and/or solar panels near the test masses within the spacecraft. After reaching the final orbits, the spacecraft positions will evolve under gravitational forces only. Micronewton ion thrusters will be used to keep the spacecraft centered about the shielded test masses within each spacecraft.

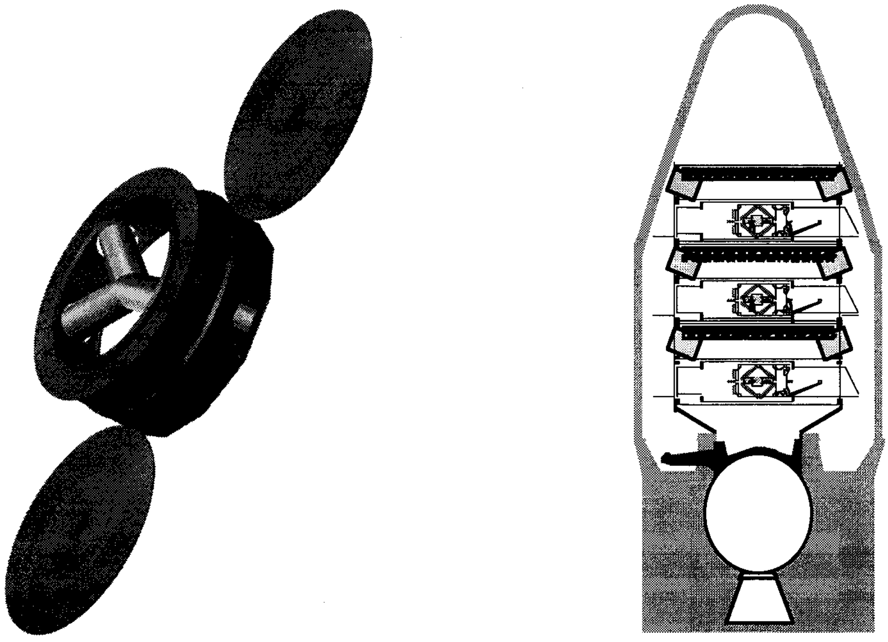

FIGURE 4.a) Artist's concept of the LISA spacecraft attached to the solar-electric propulsion module. The ion-engine is mounted at an angle to the wall of the main cylinder of the propulsion module in order to thrust through the combined center of mass. The ion engine requires power from two deployable solar arrays which are gimbaled to allow for tracking the Sun. Not shown is a cover over the top of the cylinder that prevents sunlight from striking the Y-shaped payload enclosure. b) Launch configuration for the three LISA spacecraft, each with attached propulsion module, within the 2.9 m (9.5-foot) fairing for the Delta-II 7925H. The propulsion module indicated includes two xenon-ion thrusters with two deployable solar panels in the stowed position. The spacecraft assembly is attached to the upper stage by a custom launch adapter.

MISSION OPERATIONS

The LISA mission collects data at a fairly low rate, making about ten measurements per second of the difference in distance between pairs of spacecraft. The data can be compressed using on-board algorithms to give a science data rate of 100 bits per second. Another 100 bits per second may be used for spacecraft and instrument monitoring purposes. The data can be stored on board indefinitely, although it is desirable to transmit the data to Earth at least weekly to monitor spacecraft and instrument performance. Nominally data from each spacecraft will be transmitted to the Earth through a 30 cm diameter antenna on the spacecraft to a 34 m antenna of the NASA Deep Space Network, using a data rate of 7000 bits per second with each spacecraft transmitting for 2.5 hours every other day over the mission lifetime.

CONCLUSION

The three-spacecraft mission design was refined through discussion with spacecraft design engineers of the Jet Propulsion Laboratory's Advanced Concepts Project Design Team. A short mission study was carried out to determine the feasibility of the mission design and to form preliminary subsystems designs. The results from the study are given in (4). More information about the current LISA mission design and science objectives can be found in (5) and at the web site; **http://lisa.jpl.nasa.gov**.

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